

FIELD GRADING IN CAPACITOR MARGINS

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This paper includes some of the results of modeling electric fields in the margin of a bogey plastic film liquid impregnant capacitor in which effects of foil edge shape, different impregnants, and grading wires are examined. It will be concluded that placement tolerance and connection problems make grading wires impractical and that folded foil edges are still the best solution to field grading.

High energy-density capacitors for pulse discharge are in general constructed of cylindrically wound plastic film, aluminum foil, and liquid impregnant. When quality control is exercised in manufacture,¹⁻³ capacitor failures tend to occur from corona discharge at the foil edges in the capacitor margin. Figure 1 shows a cross section of several layers of a plastic film liquid impregnant capacitor. The film

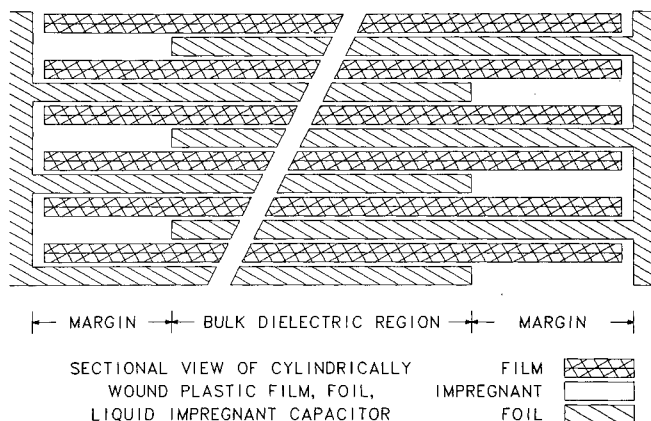


Fig. 1. Cross section of several layers of cylindrically wound capacitor.

may be several layers of polypropylene, polysulfone, or other similar material with a high dielectric strength and modest dielectric constant. The liquid insulating impregnant needed to displace all ionizable gas in the capacitor may be silicone oil, fluorinert, monoisopropyl biphenyl (MIPB), castor oil, or other fluids selected for their dielectric strength, dielectric constant, ability to impregnate, chemical compatibility in the presence of high fields, self-healing ability, propensity to form gas, and the like. In order to develop higher energy-density capacitors, it appeared appropriate initially to carry out a detailed study of maximum fields developed for various foil edge shapes with various impregnants in an otherwise specific bogey capacitor structure.

The bogey capacitor geometry that was selected had a solid dielectric thickness of 1 mil, representing two 0.5 mil polypropylene films, and a 0.1 mil impregnant layer next to the foil. The foil thickness was fixed at 1 mil, which could represent a single cut foil or a 0.5 mil folded foil. Thus in the bulk capacitor there was a 1.2 mil spacing between foils of opposite potentials.

Foils are cut by shearing or by melting with lasers or electrical discharge. Figure 2 shows six shapes for foil edges selected as representative of most possible configurations. Each corner was

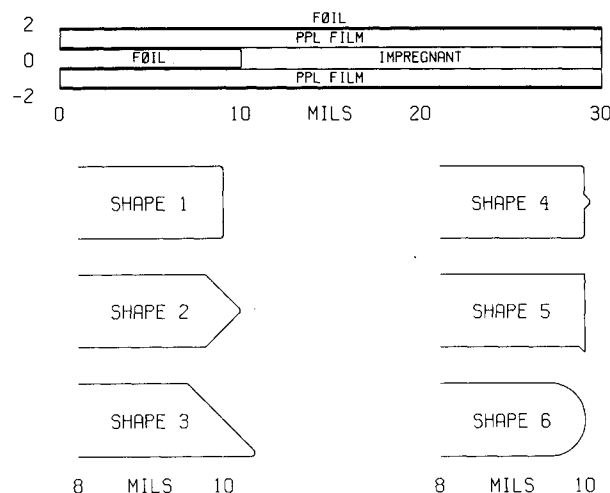


Fig. 2. Capacitor model with six foil edges.

rounded with a known radius to allow exact specification of the electric field on the foil edge, since perfectly sharp corners lead to singularities in the surface field. Radii of 0.01 and 0.05 mils were used and the functional variation of field with radius on the corners was also determined. The geometry for modeling is shown with corner radii of 0.05 mils at the top of Fig. 2. At the horizontal coordinate of 0 mils, the field was forced to be vertical. At 30 mils, the potential was set to zero along the vertical boundary, representing the grounded connection. The potential was zero well before 30 mils, so the solution is good for longer margin widths.

The energy density achievable in the bulk plastic film has been shown to be limited by the maximum electric field present in the impregnant,^{2,3} since the sharpest edges occur on the foil edge. Fields in the impregnant can be suppressed to the extent the impregnant's dielectric constant is greater than that of the plastic film. Likewise, appropriate shaping of the foil edge or addition of smooth conducting material in the margin near the foil edge can serve to grade the field. In order to model these effects in a realistic capacitor, it is necessary to be able to calculate electric fields in the dielectric materials present.

For the representative geometries selected, no analytic solution exists for the electric fields, thus requiring computer solutions to the problem. Fortunately in a problem such as this, containing multiple regions with uniform permittivity in each region, experience to date indicates the maximum field in each region must occur on the boundary. Thus it is only necessary to compute the electric field along the foil edges and along the interface between the impregnant and plastic film.

The solution of the Laplace equation yielding the potential and electric fields inside the capacitor section was obtained using Green's third formula,⁴ which gives the potential, ϕ , in a closed region as a function of the potential and its normal derivative around the boundary, S .

$$\phi(x,y) = \frac{1}{2\pi} \int_S \left[\ln\left(\frac{1}{r}\right) \frac{\partial \phi}{\partial n} - \phi \frac{\partial}{\partial n} \ln\left(\frac{1}{r}\right) \right] dS \quad (1)$$

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| 14. ABSTRACT Airborne power supplies and equipment which supply megawatts of power at tens of kilovolts require designs of minimum weight and volume which imply compact systems with high density packaging. This is especially a concern of high voltage electrical components. This paper describes high voltage tests, test parameters, and the test results for capacitors, cables, and magnetic devices. In addition, the value of dielectric withstanding voltage tests compared to surge tests and partial discharge tests is discussed. | | | | | |
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Here r is the distance from the point x, y to a point on the boundary and n is the coordinate normal to the boundary. The computer program (LAPLDDC)

written by John Hayes⁵ was utilized to calculate the fields on the boundary of each dielectric region, where the maximum field must occur. All boundary segments used were straight lines, circles, or arcs of circles. Potentials and their normal derivatives were represented along the boundary at a finite number of points. Typically several hundred points were used on the boundaries to represent the complete capacitor.

For boundary conditions either the potential or the normal derivative of potentials must be specified. Where two dielectrics interface, the dielectric constants of each are needed to force the normal component of displacement to be continuous. The code applies Equation (1) at every point along the

boundaries to determine $\frac{\partial \phi}{\partial n}$ if ϕ is given or ϕ if $\frac{\partial \phi}{\partial n}$ is given. Once ϕ and $\frac{\partial \phi}{\partial n}$ are known at every point on the boundaries, the potential and the field components $-\frac{\partial \phi}{\partial x}$ and $-\frac{\partial \phi}{\partial y}$ may be determined anywhere inside a dielectric region. However, the fields along conductive boundaries, namely $\frac{\partial \phi}{\partial n}$, are already available and the fields along dielectric interfaces can be computed from the tangential field $\frac{\partial \phi}{\partial s}$ and normal field $\frac{\partial \phi}{\partial n}$. To make contour potential plots, the potential is evaluated at points on a rectangular lattice from which the contours are plotted.

To visualize explicitly the effects of different foil edges and different impregnants in a film capacitor, polypropylene film of 1 mil total thickness was used with 1 mil foil thickness and 0.1 mil impregnant between film and foil. Impregnant also filled the margin.

For each choice of impregnant there is an assumed dielectric strength that the maximum field should not exceed, or breakdown occurs. This limit sets the electric field in the polypropylene film, wherein the bulk of the energy is stored.

Figure 3 shows a potential map of Shape 3, the 45° shear with 0.01 mil corner radii and shows representative fields going around the foil edge for 1000 V across the opposite foils. The field enhancement

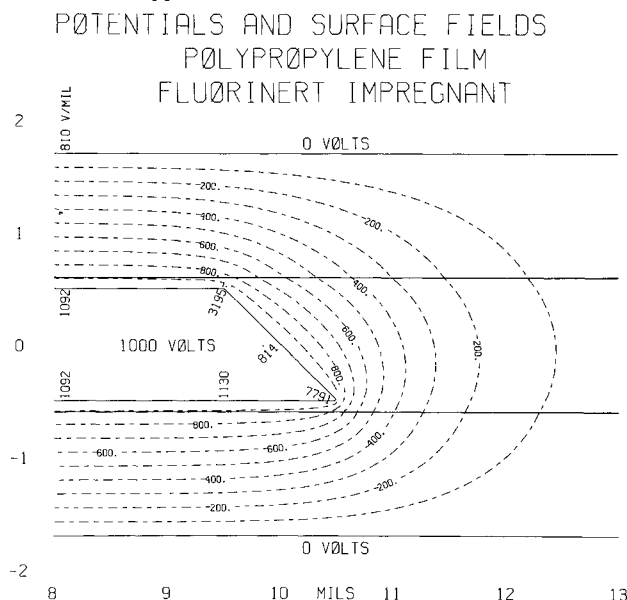


Fig. 3. Potentials and representative fields near foil edge for 1000 V on Shape 3.

factor of the foil edge is defined as the ratio of the maximum field to the field in the impregnant in the parallel section. In Figure 3 the enhancement factor is 7791/1092 or 7.13. This factor, as will be seen, is useful in comparing different foil edges in the same impregnant but not in comparing different impregnants.

Calculations similar to those illustrated in Fig. 3 were executed for the six foil edge shapes with two different corner radii and for six representative impregnants: fluorinert, transformer oil, MIPB, silicone oil, castor oil, and glycol. Figure 4 shows how glycol with a dielectric constant

EQUIPOTENTIALS FOR 1000 V ON FOIL
POLYPROPYLENE FILM
GLYCOL IMPREGNANT

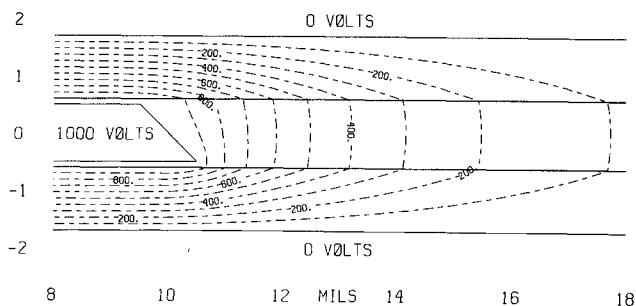


Fig. 4. Effect of a high dielectric constant ($K=39$) on potentials around Shape 3.

of 39 would reduce the field in the margin. Tables I and II show the bulk field in the polypropylene and energy density including foil mass but excluding

| | | TABLE I | | FLUORINERT | | TRANSFORMER OIL | | MIPB | |
|-------|--------|----------------------|-------------------------------|---|-------------------------------|--|-------------------------------|---|-------------------------------|
| | | | | $K = 1.89$ $D_s = 11000 \text{ V/mil}$ | | $K = 2.20$ $D_s = 1000 \text{ V/mil}$ | | $K = 2.66$ $D_s = 400 \text{ V/mil}$ | |
| SHAPE | RADIUS | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg |
| 1 | .01 | 1580. | 14.0 | 159.9 | .146 | 73.1 | .030 | | |
| | .05 | 2646. | 39.2 | 267.9 | .410 | 122.4 | .083 | | |
| 2 | .01 | 1844. | 19.1 | 177.7 | .180 | 76.5 | .032 | | |
| | .05 | 3112. | 54.3 | 299.9 | .513 | 129.1 | .092 | | |
| 3 | .01 | 1143. | 7.3 | 113.2 | .073 | 50.3 | .014 | | |
| | .05 | 2261. | 28.7 | 224.2 | .287 | 99.7 | .055 | | |
| 4 | .01 | 1609. | 14.5 | 163.0 | .152 | 74.7 | .031 | | |
| | .05 | 2669. | 39.9 | 270.5 | .418 | 123.8 | .085 | | |
| 5 | .01 | 1164. | 7.6 | 121.8 | .085 | 58.0 | .019 | | |
| | .05 | N/A | N/A | N/A | N/A | N/A | N/A | | |
| 6 | | 5297. | 157.2 | 548.2 | 1.715 | 256.0 | .362 | | |

| | | TABLE II | | SILICONE OIL | | CASTOR OIL | | GLYCOL | |
|-------|--------|----------------------|-------------------------------|--|-------------------------------|--|-------------------------------|---------------------------------------|-------------------------------|
| | | | | $K = 2.8$ $D_s = 350 \text{ V/mil}$ | | $K = 3.7$ $D_s = 350 \text{ V/mil}$ | | $K = 39$ $D_s = 500 \text{ V/mil}$ | |
| SHAPE | RADIUS | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg | PPL BULK FIELD V/mil | CAPACITOR ENERGY DENSITY J/kg |
| 1 | .01 | 66. | .024 | 80.5 | .034 | 528.1 | 1.29 | | |
| | .05 | 111. | .067 | 134.5 | .095 | 812.7 | 3.07 | | |
| 2 | .01 | 68. | .025 | 76.1 | .030 | 302.1 | .42 | | |
| | .05 | 115. | .073 | 128.4 | .087 | 509.4 | 1.20 | | |
| 3 | .01 | 45. | .011 | 52.7 | .015 | 254.4 | .30 | | |
| | .05 | 90. | .044 | 104.0 | .057 | 476.3 | 1.05 | | |
| 4 | .01 | 68. | .025 | 82.5 | .036 | 554.3 | 1.43 | | |
| | .05 | 112. | .069 | 136.4 | .098 | 849.3 | 3.35 | | |
| 5 | .01 | 53. | .016 | 68.5 | .025 | 529.7 | 1.30 | | |
| | .05 | N/A | N/A | N/A | N/A | N/A | N/A | | |
| 6 | | 232. | .294 | 265.9 | .372 | 1032.2 | 4.94 | | |

margin and container mass when the maximum impregnant field is equal to the assumed dielectric strength, D_s , indicated in the tables.² The bulk energy density, W , can be shown to be given by







$$W = \frac{1}{2} \epsilon_p E_p^2 \left[\frac{t_p + (\epsilon_p / \epsilon_I) t_I}{\rho_p t_p + \rho_I t_I + \rho_f t_f} \right] \quad (2)$$

where the subscripts refer to p - polypropylene, I - impregnant, and f - foil; ϵ is the permittivity; t the thickness; and E the field. The dielectric strength of certain impregnants is a strong function of thickness.⁶ For example, recent experiments utilizing fluorinert yield data consistent with around 11000 V/mil breakdown strength in impregnant thicknesses of less than 1 mil decreasing to 500 V/mil in 1-cm thickness.^{3,6} Standard dielectric strength tests with 1 inch spheres at 1 cm spacing are not applicable for thicknesses less than 1 mil. The data used for dielectric strengths are what were available then.

From the results of Tables I and II, the importance of a high dielectric strength for the impregnant is clearly evident. Even with the best impregnant and the rounded Shape 6, the ultimate dielectric strength of 9600 V/mil in polypropylene is not exceeded. Note also that differences between 0.01 and 0.05 mil radii of curvature on corners on the different shapes can affect the energy density by factors of 2.7 to 3.9. The folded foil, as was pointed out by Mandelcorn⁷ and Parker,¹ has a substantial improvement in energy density over bare cut edges.

The energy densities in Tables I and II are on the order of a hundred times greater for fluorinert than for the other impregnants because of the high dielectric strength assumed (11000 V/mil). Since effective dielectric strengths for other impregnants in thin thicknesses may be substantially higher than bulk strengths, the effects of foil edges and dielectric constant were analyzed several other ways. In Table III the field in the PPL film was taken to be 1000 V/mil, as used in many high-repetition-rate

TABLE III
MAXIMUM FIELD IN IMPREGNANT
(V/mil)
(for 1000 V/mil in PPL, $K_{IMP} = 2.55$)

| SHAPE | | $K_{IMP} = 1.89$ | 2.2 | 2.66 | 2.8 | 3.7 | 39. | |
|---|---|------------------|------|------|------|------|------|------|
|  | 1 | .01 | 6961 | 6253 | 5471 | 5278 | 4345 | 947 |
| | | .05 | 4157 | 3733 | 3267 | 3152 | 2602 | 615 |
|  | 2 | .01 | 5965 | 5627 | 5230 | 5128 | 4599 | 1655 |
| | | .05 | 3535 | 3334 | 3099 | 3038 | 2725 | 981 |
|  | 3 | .01 | 9622 | 8835 | 7953 | 7732 | 6647 | 1965 |
| | | .05 | 4864 | 4460 | 4013 | 3903 | 3365 | 1050 |
|  | 4 | .01 | 6835 | 6133 | 5358 | 5167 | 4243 | 902 |
| | | .05 | 4122 | 3697 | 3231 | 3117 | 2567 | 589 |
|  | 5 | .01 | 9454 | 8210 | 6891 | 6574 | 5107 | 944 |
| | | .05 | N/A | N/A | N/A | N/A | N/A | N/A |
|  | 6 | | 2077 | 1824 | 1563 | 1509 | 1316 | 484 |
| RADIUS MILS | | | | | | | | |

plastic film liquid impregnant capacitors. Here we see how the maximum field in the impregnant varies with the different shapes and with different dielectric constants. Several conclusions may be drawn.

The highest field for a given dielectric constant occurs at the 45° angle of Shape 3. Shape 2 acts to reduce the maximum field from that of a

square cut (Shape 1). The maximum field on Shape 2 occurs in the 90° corner in the center. The projection at the center of the foil edge in Shape 4 extending 0.1 mil at 45° and meeting in a 90° corner, serves to slightly shield the charge build-up on the two corners as the projection itself is shielded by the surrounding edge. Thus, the peak field, though still at the outside corners, is reduced from that of Shape 1 and the PPL energy density is slightly higher

The 45° projection at the lower corner in Shape 5 makes the maximum field higher than on the 90° corner in Shape 1 but less than the 45° corner of Shape 3 where there are no nearby concave corners to shield the tip. As expected, Shape 6 allows the highest energy density.

TABLE IV
ENHANCEMENT FACTOR







| SHAPE | | K_{IMP} = 1.89 | 2.2 | 2.66 | 2.8 | 3.7 | 39. | |
|---|---|------------------|------|------|------|------|------|------|
|  | 1 | .01 | 5.16 | 5.39 | 5.71 | 5.80 | 6.30 | 14.5 |
| | | .05 | 3.08 | 3.22 | 3.41 | 3.46 | 3.78 | 9.4 |
|  | 2 | .01 | 4.42 | 4.85 | 5.46 | 5.63 | 6.67 | 25.3 |
| | | .05 | 2.62 | 2.88 | 3.23 | 3.34 | 3.95 | 15.0 |
|  | 3 | .01 | 7.13 | 7.62 | 8.30 | 8.49 | 9.64 | 30.1 |
| | | .05 | 3.61 | 3.85 | 4.19 | 4.29 | 4.88 | 16.1 |
|  | 4 | .01 | 5.07 | 5.29 | 5.59 | 5.67 | 6.16 | 13.8 |
| | | .05 | 3.06 | 3.19 | 3.37 | 3.42 | 3.72 | 9.0 |
|  | 5 | .01 | 7.01 | 7.08 | 7.19 | 7.22 | 7.41 | 14.4 |
| | | .05 | N/A | N/A | N/A | N/A | N/A | N/A |
|  | 6 | | 1.54 | 1.57 | 1.63 | 1.66 | 1.91 | 7.4 |
| RADIUS MILS | | | | | | | | |

Table IV shows the enhancement factor, the ratio of maximum impregnant field to bulk impregnant field, for the various shapes. For a given dielectric constant, this factor serves well to compare effects of foil edge shape; however, it gives a distorted view of effects of different dielectric constants relative to the plastic film since the higher dielectric constant tends to suppress the impregnant field more in the bulk than around the foil edge. As the impregnant dielectric constant increases relative to that of the film, the field in the impregnant is suppressed. Thus for a given dielectric stress, a higher impregnant dielectric constant will allow higher energy densities.

While maximum fields in the impregnant have been presented for two radii of curvature and for several specific dielectric constants, in examining the results for other radii and dielectric constants, the maximum field, E_{max} , for Shapes 1 to 5 could be approximately expressed as a function

$$E_{max} = A \left(\frac{K_{imp}}{K_{film}} \right)^{-B} \left(\frac{r}{0.01} \right)^{-\alpha} \quad (3)$$

where K_{imp}/K_{film} is the impregnant to film dielectric constant ratio and r is the radius of curvature in mils. Table V gives values of A , B , and α for the five shapes. The fields on the 45° projection of Shapes 3 and 5 have a stronger inverse dependence on radius ($\alpha \approx 0.42$) than on the 90° projections of Shapes 1, 2, and 4 ($\alpha \approx 0.32$).

TABLE V

Parameter Values for Equation 3

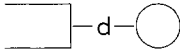
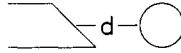
| Shape | A (V/mil) | B | α |
|-------|-----------|-------|----------|
| 1 | 4682 | 0.623 | 0.32 |
| 2 | 4409 | 0.386 | 0.325 |
| 3 | 6773 | 0.488 | 0.424 |
| 4 | 4593 | 0.633 | 0.314 |
| 5 | 5986 | 0.728 | 0.431 |

While a high permittivity impregnant will grade the field at a foil edge, such impregnants may not have other necessary characteristics. Glycol, for instance, does not wet or impregnate the capacitor well (refer to Figs. 3 and 4).

The effect of placing a conducting wire whose diameter equaled the foil thickness in the margin parallel to the edge was computed for Shapes 1 and 3 in fluorinert. Table VI gives the maximum field on the foil edge or wire as a function of distance from center foil edge to wire edge. Note that it would be necessary to position the wire with a tolerance of a few tenths of a mil to insure limiting the maximum field.

TABLE VI

MAXIMUM FIELD WITH 1 MIL GUARD WIRE
RADIUS = 0.01

| |  |  |
|---------|---|---|
| d(mils) | E_{max} (V/mil) | E_{max} (V/mil) |
| 0.25 | 3288 | ---- |
| 0.5 | 3623 | 3074 |
| 0.75 | 3916 | 3659 |
| 1.0 | 4189 | 4238 |
| 1.25 | 4436 | 4801 |
| 1.5 | 4649 | 5311 |
| 2.5 | 5243 | 6775 |
| 20.0 | 5637 | 7792 |

The potential of the wire was held to the center foil potential of 1000 V in these calculations. If the wire is allowed to float, the potential drops to much lower value increasing the field. Figure 5 demonstrates for a wire 0.25 mil edge to edge from Shape 1 that a floating wire will have a potential of 530 V and will allow a maximum field of 5851 V/mil, up from 3288 V/mils. Unfortunately, one cannot tie the wire at foil potential during a transient since the current flows at right angles to the wire in the foil, but must be constrained to follow the wire to a connection to the foil.

It is concluded that wires are an impractical solution to field grading both from position tolerance and from electrical connection aspects. While high dielectric constant impregnants will grade the field, no suitable material is known at present. Thus folded foils are the best solution presently available.

SHAPE 1 0.25 MIL GAP TO WIRE
POLYPROPYLENE + FLUORINERT
FIXED AND FLOATING GUARD

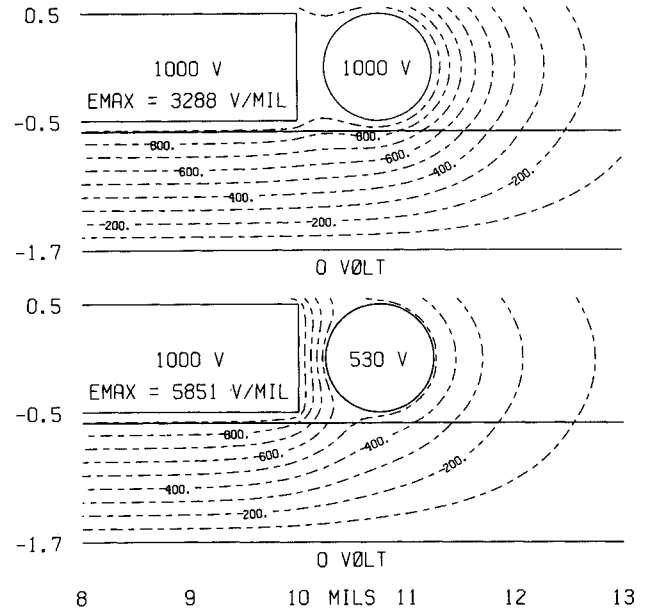


Fig. 5. Equipotentials and maximum field for Shape 1 with guard wire.

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